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CARBIDE FUEL PIN AND CAPSULE DESIGN FOR IRRADIATIONS AT THERMIONIC TEMPERATURES

by Byron L. Siegel, Jack G. Slaby, William F. Mattson, and Dominic C. DiIanni

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16. Abstract
The design of a capsule assembly to evaluate tungsten-emitter - carbide-fuel combinations for thermionic fuel elements is presented. An inpile fuel pin evaluation program concerned with clad temperature, neutron spectrum, carbide fuel composition, fuel geometry, fuel density, and clad thickness is discussed. The capsule design was a compromise involving considerations between heat transfer, instrumentation, materials compatibility, and test location. Heat-transfer calculations were instrumental in determining the method of support of the fuel pin to minimize axial temperature variations. The capsule design was easily fabricable and utilized existing state-of-the-art experience from previous programs.

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SUMMARY

An experimental program to evaluate the tungsten-emitter - carbide-fuel combinations for thermionic fuel elements (TFE's) in support of a joint AEC-NASA thermionic reactor development program was initiated to explore variables such as clad temperature, neutron spectrum, carbide fuel combinations, fuel density, fuel geometry, and clad thickness. This report discusses the problems associated with the design of capsules and fuel pins for an in-pile test program involving these variables. The final design was a compromise between heat-transfer, instrumentation, materials-compatibility, and test location considerations. The heat-transfer calculations were instrumental in determining the method of support of the fuel pin in order to maintain acceptable axial temperature variations along the fuel pin. The capsule design was easily fabricable and utilized existing state-of-the-art experience from previous programs. Since thermionic nuclear research was discontinued by NASA, no capsules were fabricated or irradiated in this program.

INTRODUCTION

An effort was under way at the Lewis Research Center in support of the AEC sponsored program to develop a high-performance thermionic reactor. The reactor, under development by contract to Gulf General Atomic (GGA), was a flashlight type of concept with several thermionic diodes arranged in series to form a thermionic fuel element (TFE). The reactor core consisted of a large number of these thermionic fuel elements. The highly modular nature of this reactor concept permits testing of prototype TFE's. A part of the Lewis Research Center's effort was to provide technological support for the TFE development program. While selected TFE's were being tested under irradiation as operating diodes at GGA, the Lewis Research Center tests were to investigate varia-

bles as they influence dimensional stability of the emitters. These tests were to be conducted on individual fueled emitter bodies (fuel pins) under irradiation conditions but without thermionic emission.

This report discusses the design of the fuel pin and capsules intended for a test program in the NASA Plum Brook reactor facility. Because of the cancellation of the thermionic program, all fabrication contracts were terminated and no fuel pins were irradiated.

FUEL PIN AND CAPSULE ASSEMBLY DESIGN

The design of the fuel pins and capsule assemblies is shown in figure 1. The intent behind the design concept was to use the experience obtained from the design of previous irradiations programs (such as that reported in ref. 1) wherever possible. Following is a description of the salient features of the fuel pin and capsule design.

Fuel Pin Design

The fuel pins to be irradiated at Plum Brook in support of the thermionics program were two different sizes, a reference-diameter size with a 2.79-centimeter (1.1-in.) outside diameter and a half diameter size with a 1.40-centimeter (0.55-in.) outside diameter. The fuel pin design for both sizes (shown in fig. 2) basically consists of the tungsten fuel cup, nuclear fuel, plenum, and end cap.

The tungsten fuel cup was a duplex clad composed of fluoride derived vapor-deposited tungsten as the substrate covered with a layer of chloride derived vapor-deposited tungsten. The clad thickness for the reference diameter pins (0.102 cm (0.040 in.)) was twice that of the half diameter pins. Three types of uranium carbide fuel were considered for evaluation: 90 mole percent uranium carbide - 10 mole percent zirconium carbide plus 4 weight percent tungsten (90 UC-10ZrC + 4 wt. % W; 77% theoretical density), UC + 4 wt. % W (100 percent dense); and UC (100 percent dense). The ZrC and W additives stabilize the fuel by minimizing sintering as well as reducing the reaction between the fuel and clad. The fuel volume fraction for the 90 UC-10ZrC + 4 wt. % W fuel pins was 0.65 the same as for the reference reactor fuel pins. This fuel volume fraction of 0.65 and fuel density of 77 percent were used to determine the central hole size for the fuel. To determine the effect of change in fuel volume fraction one pin did not have a central hole. This increased the fuel volume fraction from 0.65 to 0.74. The total uranium content for all the other pins in table I was the same. This was achieved by varying the center hole size of the 100 percent dense fuel relative to the 77 percent dense fuel. The fuel length for the reference-diameter pin was 5.08 centi-

meters (2 in.). The fuel length of the half-diameter pin should be 2.54 centimeters (1 in.) to have the same length to diameter ratio as the reference diameter pin; however, the end peaking effects for a 2.54-centimeter (1-in.) long specimen would preclude a section with uniform power. Consequently, a compromise length of 3.81 centimeters ($1\frac{1}{2}$ in.) was used.

The upper half of the fuel pin shown in figure 2 contains the gas plenum. A plenum was used instead of a vent and was sized such that, if all the fission gas generated during the irradiation was released, the clad would creep less than 1 percent from the internal gas pressure. Three tungsten cylinders serve as both fuel positioners and baffle locators. The purpose of the baffles is to minimize free-convection current within the plenum. Belville type of washers, fabricated from the tantalum alloy T-111 (Ta-8 percent W-2 percent Hf), provide for any differential thermal expansion effects. The fuel pin is backfilled through the tantalum fill tube with argon at a pressure of approximately 25 torr. This is equivalent to 100 torr at operating temperature. At or above this pressure, the thermal conductivity of argon is almost independent of pressure. The fill tube is welded to a tantalum disk, which in turn is diffusion bonded to the tungsten end cap (see fig. 2). The fuel diameters were selected to preclude interference with the clad as a result of differential thermal expansion. The argon cover gas minimized the temperature drop across any fuel clad interface or gap. By comparison, if a vacuum existed in the gap between the fuel and the clad, the fuel center temperature would be approximately 950° C higher than with argon in the gap for a half-diameter pin. A tungsten fuel washer and spiral spring was placed at the bottom of the fuel cup to prevent the fuel from stressing the cup at the junction between the base and the cylinder.

Capsule Design

Both the instrumentation and heat-transfer requirements greatly influenced the capsule design. The high operating temperatures of the fuel pins necessitated the use of tungsten/rhenium thermocouples for direct clad temperature measurement. The shape of the tungsten fuel cup as well as considerations such as attaching and assembling the components dictated where the fuel cup thermocouple could be attached. Initial heat-transfer calculations showed that with supports on the fuel cup base (hot end) axial heat losses would cause unacceptable temperature gradients.

A stainless-steel mockup of the capsule components and fuel pin (shown in fig. 3) was made to determine if there were any fabrication or assembly problems associated with the design. Several changes resulted which made the capsules easier and less expensive to fabricate. The final design is shown in figure 1. The fuel cup is attached from the plenum end to a temperature monitoring sleeve. The sleeve in turn is sup-

ported from the capsule end cap. The method of supporting the sleeve and fuel cap is by means of two 0.081-centimeter (0.032-in.) diameter pins (see fig. 1). One high-temperature thermocouple is mechanically attached to the base of the tungsten cup. This method of attachment consists of machining two 0.026-centimeter (0.011-in.) diameter holes, using the electrical discharge method (EDM), through the base of the cup at an angle (as shown in fig. 2). A similar method of attachment was used in reference 2 to measure the temperatures of tungsten plates. The 0.025-centimeter (0.010-in.) diameter tungsten - 3-percent rhenium/tungsten - 25-percent rhenium thermocouple wires are put through these holes; the ends of the wires are then crimped. The wires are pulled back into the holes until the crimped sections are securely wedged in place. Four intermediate-temperature thermocouples (chromel alumel) are located within the sleeve at three axial locations adjacent to the fueled region of the pin. Two thermocouples are at the axial midplane of the fuel. During irradiation one of these thermocouples faces the reactor core and the other is 180° opposite. Circumferential temperature and power variations within the fuel pin can be evaluated from these thermocouples. The two remaining thermocouples are located in a plane parallel to the reactor core but axially above and below the two fuel center thermocouples by 0.954 or 1.59 centimeters (0.375 or 0.625 in.), depending on the fuel length. The sleeve thermocouples operating at approximately 800° C are considered the primary temperature monitoring instrumentation. These thermocouples are similar to those used in reference 3, which operated for 8070 hours at 1100° C without failure. The tungsten/rhenium thermocouple is used to establish a correlation with the sleeve thermocouples. This correlation was to be performed in the early part of the irradiation since the tungsten/rhenium thermocouple was not expected to last the duration of the test. All the thermocouples enter the capsule from the cold or plenum end and are completely preassembled and checked before capsule assembly. The attachment of the tungsten/rhenium thermocouple to the fuel pin base is the final step before final capsule closure.

The capsule is filled with helium, and the operating temperature of the sleeve and fuel pin is established for the design fuel power by the sizing of the stepped heat-transfer gaps between the fuel pin and sleeve and the capsule and sleeve. The axial gradients are established by the steps in the sleeve at both ends in the vicinity of the fueled region. A discussion of the heat-transfer calculations is presented in the following section.

One problem associated with the use of the monitoring sleeve to determine the fuel pin temperature is the change in emissivity of the sleeve surface with time. The carbon from the fuel (UC) diffuses through the tungsten clad and deposits on the colder sleeve. The emissivity of the sleeve could change from approximately 0.25 to a value as high as 0.90. This could decrease the clad temperature as much as 110° C while maintaining a constant sleeve temperature. An out-of-pile test was scheduled to determine the rate of change of emissivity with time but was terminated with the curtailment of nuclear work at

NASA. Methods of surface treatment to prevent sleeve emissivity changes were also being investigated.

Three 0.081-centimeter (0.032-in.) diameter pins located in the sleeve in line with the bottom of the fuel cup (see figs. 1 and 3) center the fuel pin within the sleeve and provide additional support during handling. A diametral clearance at operating temperature of 0.05 to 0.1 millimeter (2 to 4 mils) between the pins and the cup exists if all components are properly aligned.

TEST REQUIREMENTS

Table I describes the materials and test requirements for 10 fuel pins. Some of the variables to be investigated or compared are true time and accelerated burnup rates, temperature effects, fast and thermal flux tests, fuel geometry, fuel density and fuel volume fraction, fuel additives, and clad thickness.

The nominal clad temperature was 1550° C; however, one pin was to be operated at a 1425° C clad temperature. The acceptable clad temperature variation from the nominal 1550° C is $\pm 50^{\circ}$ C excluding 0.635 centimeter (1/4 in.) from each end of the fuel (see fig. 4). The clad temperature in the 0.63-centimeter (1/4-in.) fuel region adjacent to the plenum shall not drop below the acceptable clad temperature by more than 60° C. The clad temperature in the 0.63-centimeter (1/4-in.) fuel region adjacent to and including the entire cup shall be within 80° C of the acceptable clad temperature. It is believed these temperature gradients should not cause excessive thermal stresses, however, the calculations to verify this were not complete at the termination of the program. The reference fuel pins were to be operated at the reference reactor nominal burnup of 1.58×10^{20} fissions per cubic centimeter in 20 000 hours, and the half-diameter pins to the same burnup in 5000 hours for an acceleration factor of 4 on burnup rate.

The test operating conditions duplicated the fuel operating conditions in the thermionic reactor. Experience gained in a previous irradiations program, the advanced power reactor program (ref. 3) provided a realistic evaluation of the test conditions that could be achieved. The following criteria was used as an acceptable power generation variation within the fuel.

Radial power density variation, max/min	1.5
Circumferential power density variation, max/min	1.1
Axial power variation excluding 0.63 cm (1/4 in.) on each end, max/min	1.2
Axial power variation including 0.63 cm (1/4 in.) on each end, max/min	1.4

TEST FACILITY FOR THERMAL FLUX IRRADIATIONS

The thermal flux irradiations are performed in the test holes of the core side facility, which is adjacent to the core of the Plum Brook Reactor (see fig. 5). One capsule containing a reference size fuel pin or two capsules containing half-diameter fuel pins are irradiated in each test hole. The test hole assemblies containing the capsules pivot about a fulcrum point above the reactor core in such a manner that the capsules swing in arcs towards or away from the core. The combination of the large distance between capsule and fulcrum and the small distance that the capsules move (a 6° arc) results in a capsule movement which is essentially perpendicular to the core. At this test location no vertical movement of the capsules relative to the core during the reactor cycle is required. This is because the reactor flux shape does not change appreciably with control rod movements in this location. An electromechanical device is used to remotely position the test facility horizontally relative to the core during reactor operation. If two capsules are tested in the same test hole, provisions have been made to adjust their relative positions vertically between reactor cycles. This adjustment is necessary only if the capsules are operating at different fuel cup temperatures, and takes advantage of the vertical variation of the flux field.

TEST FACILITY FOR FAST FLUX IRRADIATIONS

One capsule containing either a reference-diameter or half-diameter fuel pin is irradiated in each test hole. The test locations shown in figure 5 are in the lattice and reflector pieces. The capsule is supported within a holder and moves vertically within the core by means of a vertical adjustable facility tube (VAFT) as described in reference 4. This is an electromechanical device for remotely positioning the capsule vertically. Surrounding the capsule is a neutron shield composed of cadmium and boron which screens out the thermal and epithermal neutrons. By use of this duplex shield the fast fluence damage to the tungsten fuel cup would be similar to that occurring in the reference thermionic reactor. The selection of test locations was based on the criteria that the total burnup and fast fluence damage be achieved simultaneously.

HEAT TRANSFER CALCULATIONS

A computer code, Steady State Heat Transfer Program (STHTP) (ref. 5), was used to calculate the dimensions between capsule, sleeve, and fuel pin to provide acceptable fuel pin temperatures. This program was designed to handle three-dimensional steady-

state heat-transfer cases involving internal heat generation, temperature dependent thermal conductivity, radiation heat transfer, and constant film contact coefficients.

The capsule geometry was divided into 400 nodes using a two-dimensional cylindrical coordinate arrangement (r, z) for most of the heat-transfer calculations. However, in cases where a two-dimensional model could not represent the true local temperature distribution, a three-dimensional model was used (r, z, θ). This was necessary to determine temperatures that were influenced by local perturbations such as sleeve centering pins contacting the fuel pin (fig. 1) and axial conduction losses affecting thermocouples.

Radiation heat transfer between fuel pin to sleeve to capsule wall was handled in the program as radiation between cylinders. The program cannot account for radiation heat transfer from the bottom of the fuel pin (hot end) to the capsule end cap and capsule wall. Consequently it was necessary to calculate the net radiation heat transfer from the fuel pin bottom as that from two enclosed parallel disks. A fictitious emissivity value was used to account for the heat transferred to the side walls. No radiation shields were placed between the bottom of the fuel pin and capsule end cap because the bare wire thermocouple precluded shields being located close enough to the base of the fuel pin to be effective. The radiation shields above the fuel, however, reduced the radiation heat loss at the top end of the fuel pin. The heat transferred by radiation was approximately 20 percent of the total heat transferred for the reference diameter fuel pin and 10 percent for the half diameter fuel pin.

Contact coefficients were used where applicable and were calculated based on design tolerances.

Temperatures in the fuel pin and the sleeve were controlled by varying the radial dimensions of the sleeve and capsule. In this manner the heat conduction resistances (gas gaps) were adjusted to provide acceptable axial temperature distribution. To compensate for end losses, it was necessary to increase the thermal resistance (larger gas gap) near the ends of the fuel pins in an attempt to maintain acceptable temperature profiles as specified in figure 4.

This increase of thermal resistance (gap size)near the ends was accomplished by stepping the inside diameter of the sleeve and also the inside diameter of the capsule wall. Centering pins were designed to minimize axial conduction losses from fuel pin to sleeve. However, because of fabrication considerations the resulting size of the centering pins was a compromise. It was found that the temperature gradient on the end cap caused by the heat loss from the three centering pins was very localized. A thermocouple in the sleeve positioned between the pins was beyond these perturbed regions. The fuel pin end cap average temperature was lowered, however, by about 31° C due to the presence of, but not contact with, the centering pins. There was a design radial clearance of 0.025 to 0.05 millimeter (1 to 2 mils) at operating temperature between

each centering pin and the fuel pin end cap. Due to uncertainties associated with these clearances the effect on end cap temperature was investigated. Since the fuel pin was to be mounted in a vertical position the most probable situation would be for the fuel pin end cap to be in contact with two of the three centering pins. For this case the calculated end cap temperature was lowered an additional 28° C.

Figure 6 shows the fuel pin clad temperature profile along the axial length of the fuel pin. The temperature drop at the ends is somewhat larger than desired, but to further flatten the profile would necessitate design compromises that would invalidate the integrity of the experiment.

Figure 7 shows the various temperature drops in the radial direction for a reference-diameter fuel pin from the fuel inside diameter to the outer wall of the stainless-steel capsule. Reactor primary cooling water at 65° C (150° F) having a calculated heat-transfer coefficient of 1.7 watts per square centimeter per $^{\circ}$C (3000 Btu/hr-ft^2-$^{\circ}$F) cools the capsule outer wall.

CONCLUDING REMARKS

Some of the problems associated with inpile evaluation of high-temperature fuel pins for thermionic reactor application are discussed and incorporated into a fuel-pin - capsule design. The final design was a compromise between heat transfer, instrumentation, materials compatibility, and test location considerations. The heat-transfer calculations were instrumental in determining the method of support of the fuel pin to maintain acceptable axial temperature variations along the fuel pin. This also limited the number of thermocouples and the methods of attaching the thermocouples to the fuel pin. The final design met all the desired criteria, was easily fabricable, and utilized existing state-of-the-art experience from previous programs.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 28, 1973,
503-25.

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TABLE I. - FUEL PIN MATERIAL AND REQUIREMENTS

Pin number	Material	Volume fraction, percent	Density, percent of theoretical	Fuel: Outside diameter, cm	Fuel: Outside diameter, in.	Fuel: Inside diameter, cm	Fuel: Inside diameter, in.	Fuel volume, cm^3
511-1	90 UC-10 ZrC + 4 W	65.0	77	2.568	1.011	0.907	0.357	22.6
511-2				2.568	1.011	.907	.357	22.6
512-1				1.283	.5051	.452	.178	4.24
512-2				1.285	.5060	.460	.181	4.24
512-3				1.283	.5051	.452	.178	4.24
512-4		74.2		1.283	.5051	-----	-----	4.842
522-1	UC + 4 W	66.7	100	1.283	0.5051	0.704	0.277	3.346
522-2		58.6		1.283	.5051	.805	.317	2.935
522-3		63.4		1.233	.4853	.709	.279	2.935
522-4		58.5		1.285	.5060	.798	.314	2.935
532-1	UC	57.0	100	1.283	0.5051	0.810	0.319	2.862

Pin number	Material	Clad: Inside diameter, cm	Clad: Inside diameter, in.	Clad: Thickness, cm	Clad: Thickness, in.	Fission power,[b] W/cm^3	Burnup, $fissions/cm^3$	Planned time, hr
511-1	90 UC-10 ZrC + 4 W	2.591	1.020	0.102	0.040	61.8	1.578×10^{20}	20 000
511-2		2.591	1.020	.102	.040	61.8		20 000
512-1		1.295	.510	.051	.020	247.2		5 000
512-2						247.2		
512-3						247.2		
512-4						216.3	1.381	
522-1	UC + 4 W	1.295	0.510	0.051	0.020	313.1	1.998	5 000
522-2		1.295	.510	.051	.020	357.5	2.280	
522-3		1.245	.490	.076	.030	357.5	2.280	
522-4		1.295	.510	.051	.020	357.5	2.280	
523-1	UC	1.295	0.510	0.051	0.020	366.0	2.336	5 000

[a]Clad operating temperature 1825° K except for fuel pin 512-2 for which it is 1700° K.
[b]Heat flux ~ 94.3 W/cm^2 for all fuel pins except for pins 511-1 and 511-2 for which it is 62.7 W/cm^2.

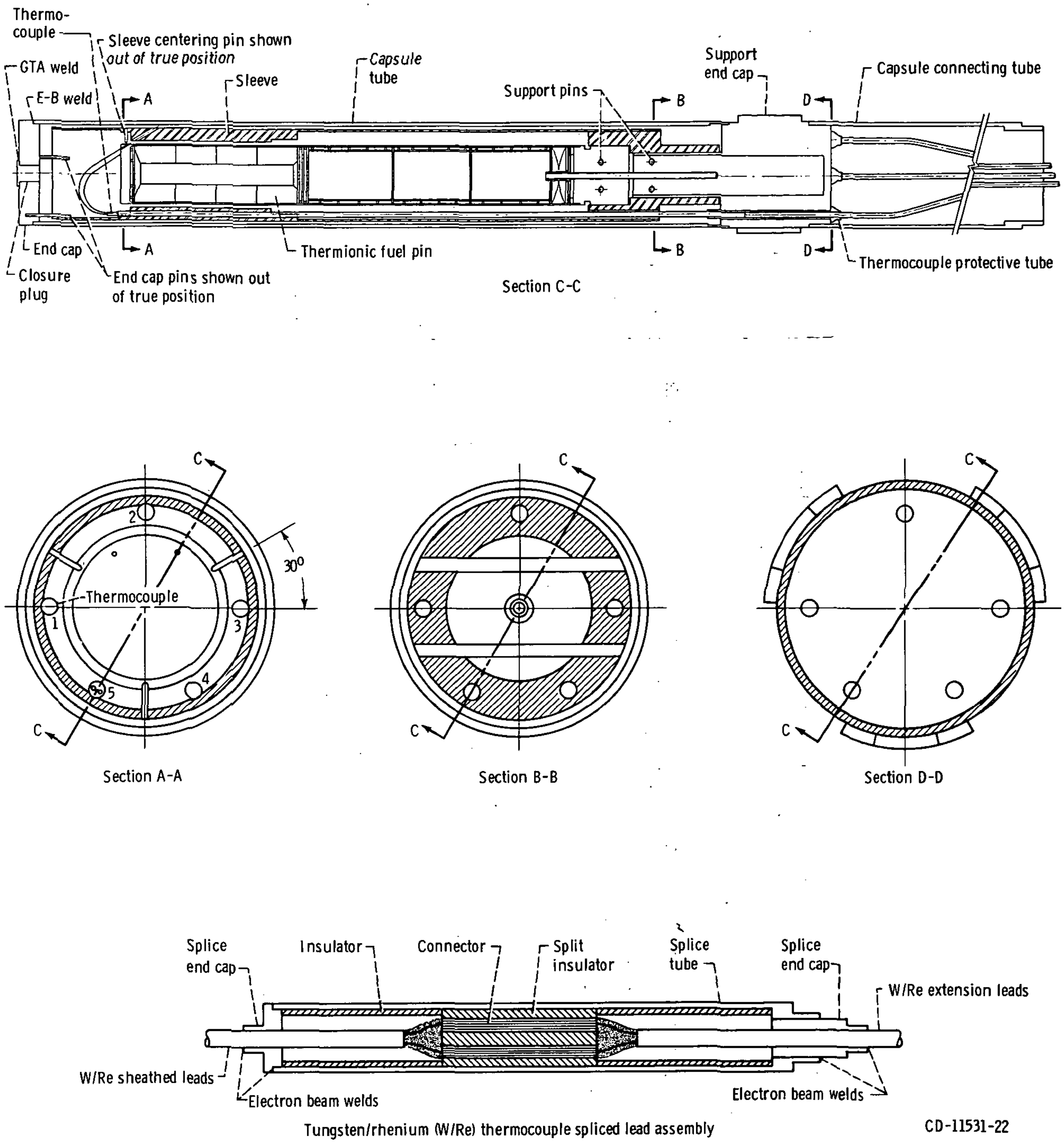

Figure 1. - Thermionic capsule and fuel pin assemblies.

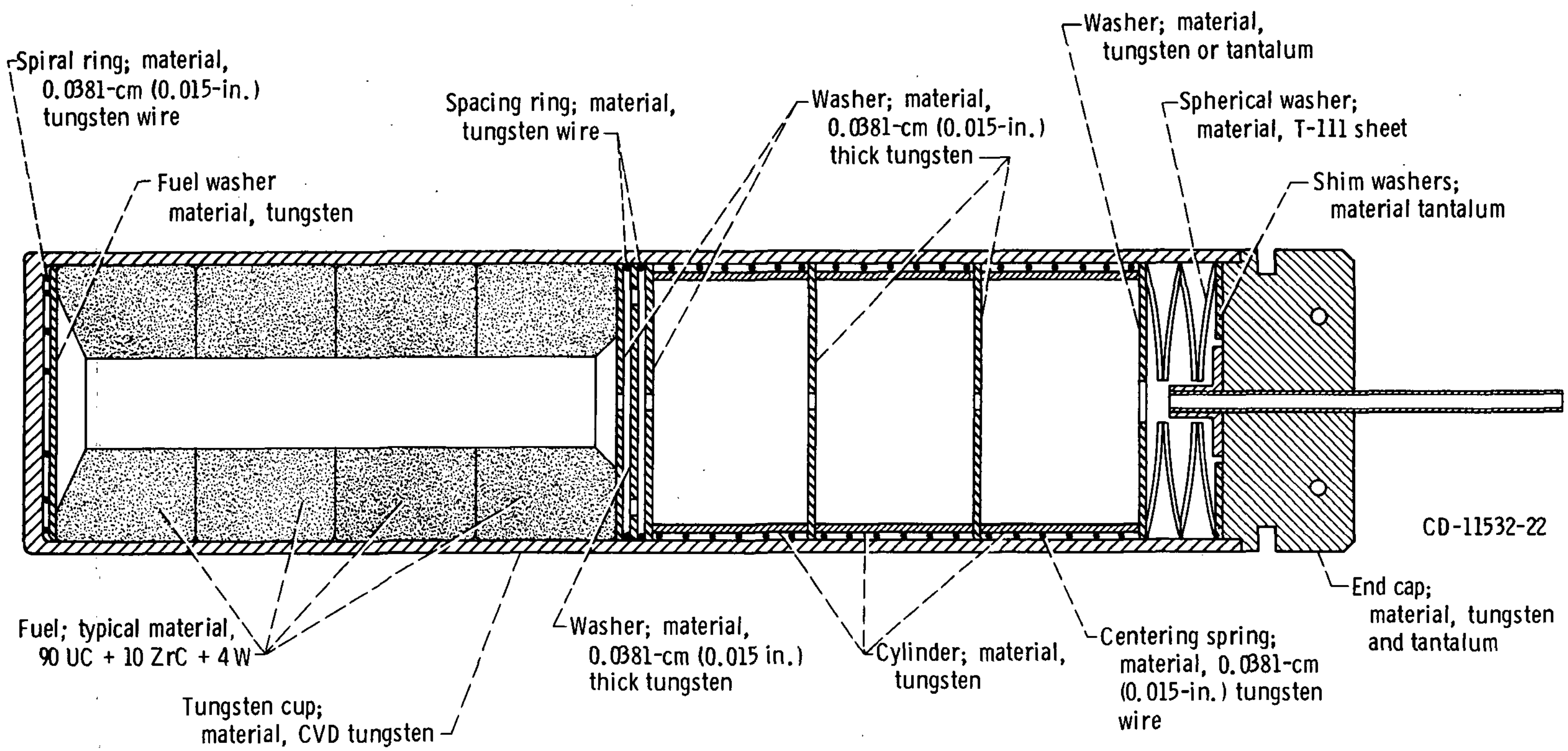

Figure 2. - Thermionic fuel pin.

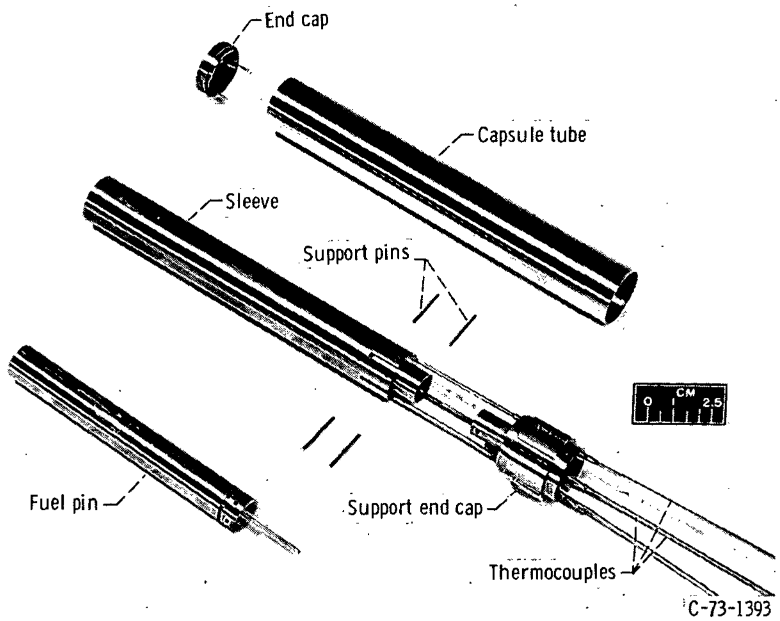

Figure 3. - Capsule assembly.

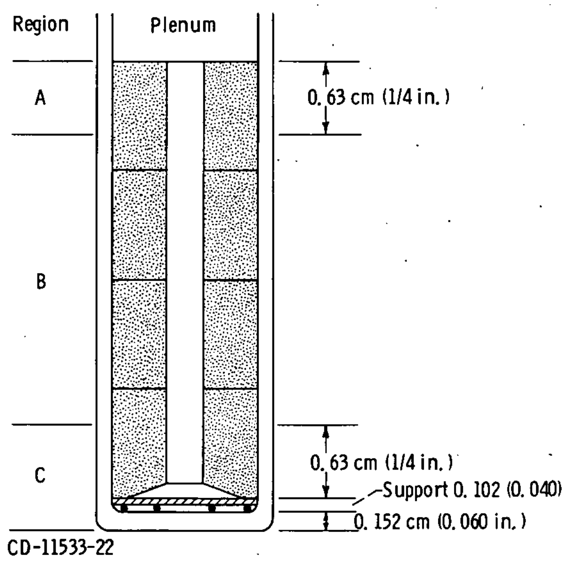

Figure 4. - Acceptable clad temperature variation. Temperature constraints: region B shall be $1550 \pm 50^\circ$ C; region A, within 60° C of the temperature at the interface between regions A and B; and region C, within 80° C of the temperature at the interface between regions B and C. The temperature throughout all regions shall not exceed 1600° C.

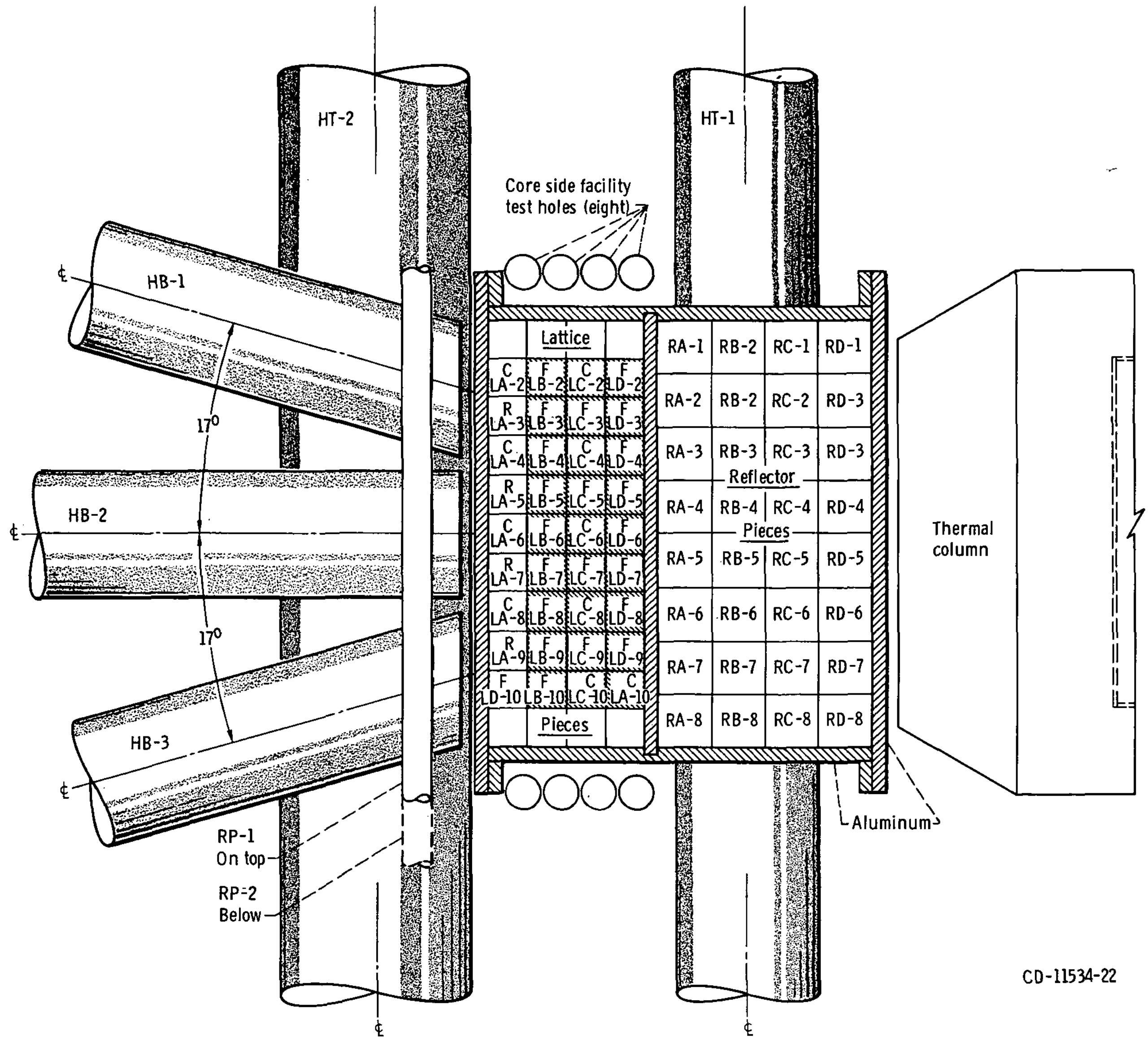

Figure 5. - Reactor core, horizontal section of Plum Brook reactor facility.

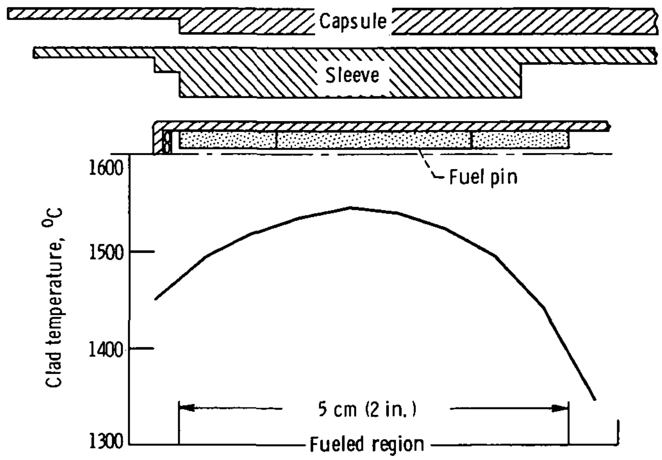

Figure 6. - Calculated fuelpin clad axial temperature distribution for reference-diameter capsule.

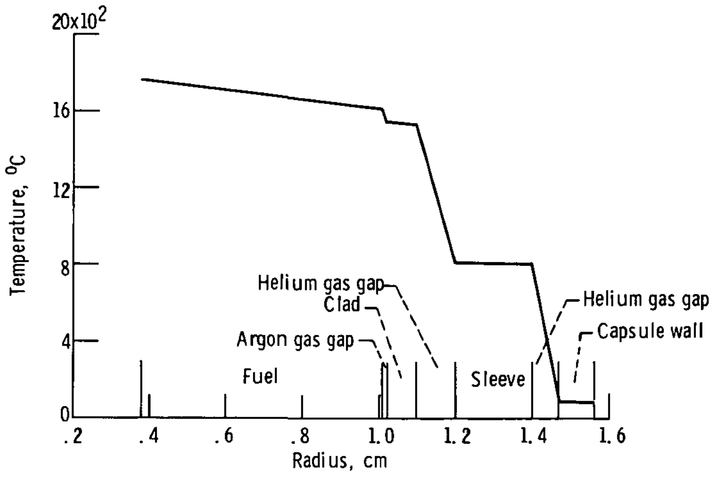

Figure 7. - Calculated radial temperature distribution taken at axial mid-plane of fuel for reference-diameter capsule.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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